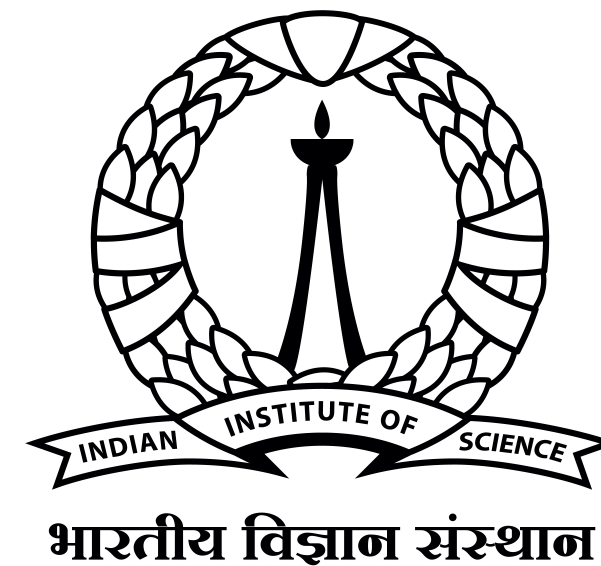
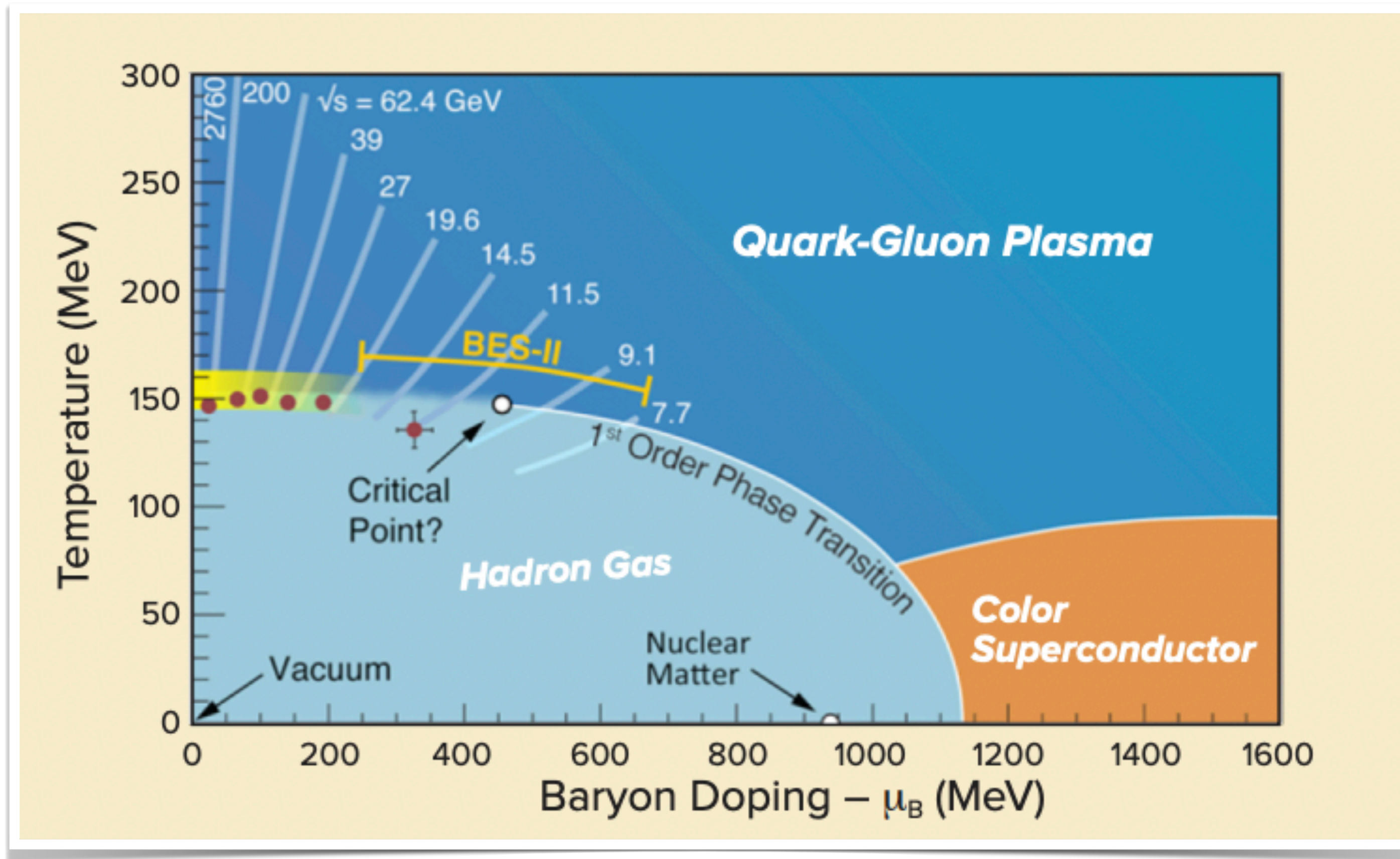


Mapping the phase diagram of Quantum Chromodynamics via heavy-ion collisions

Maneesha Sushama Pradeep
Center for High Energy Physics, Indian Institute of Science



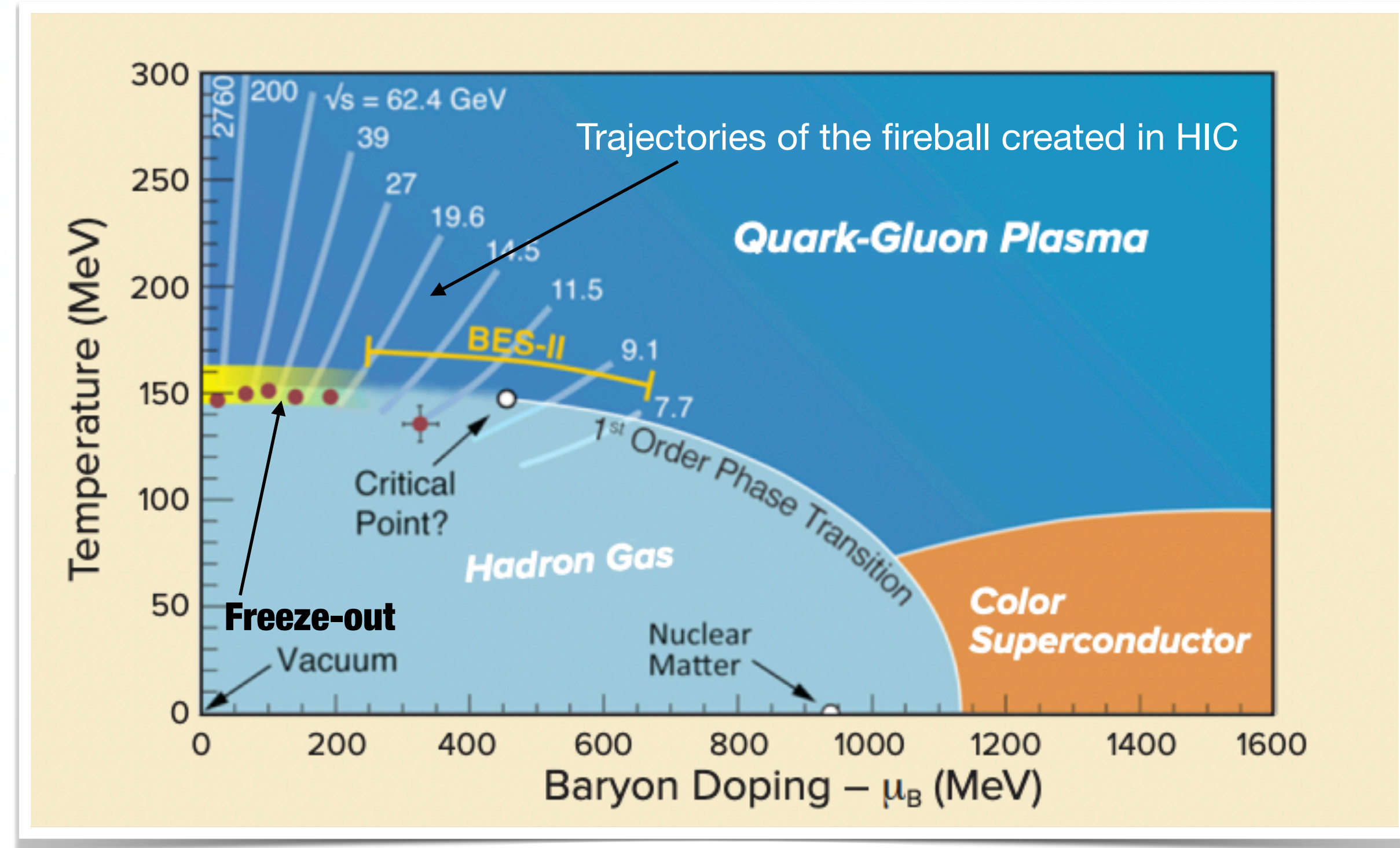
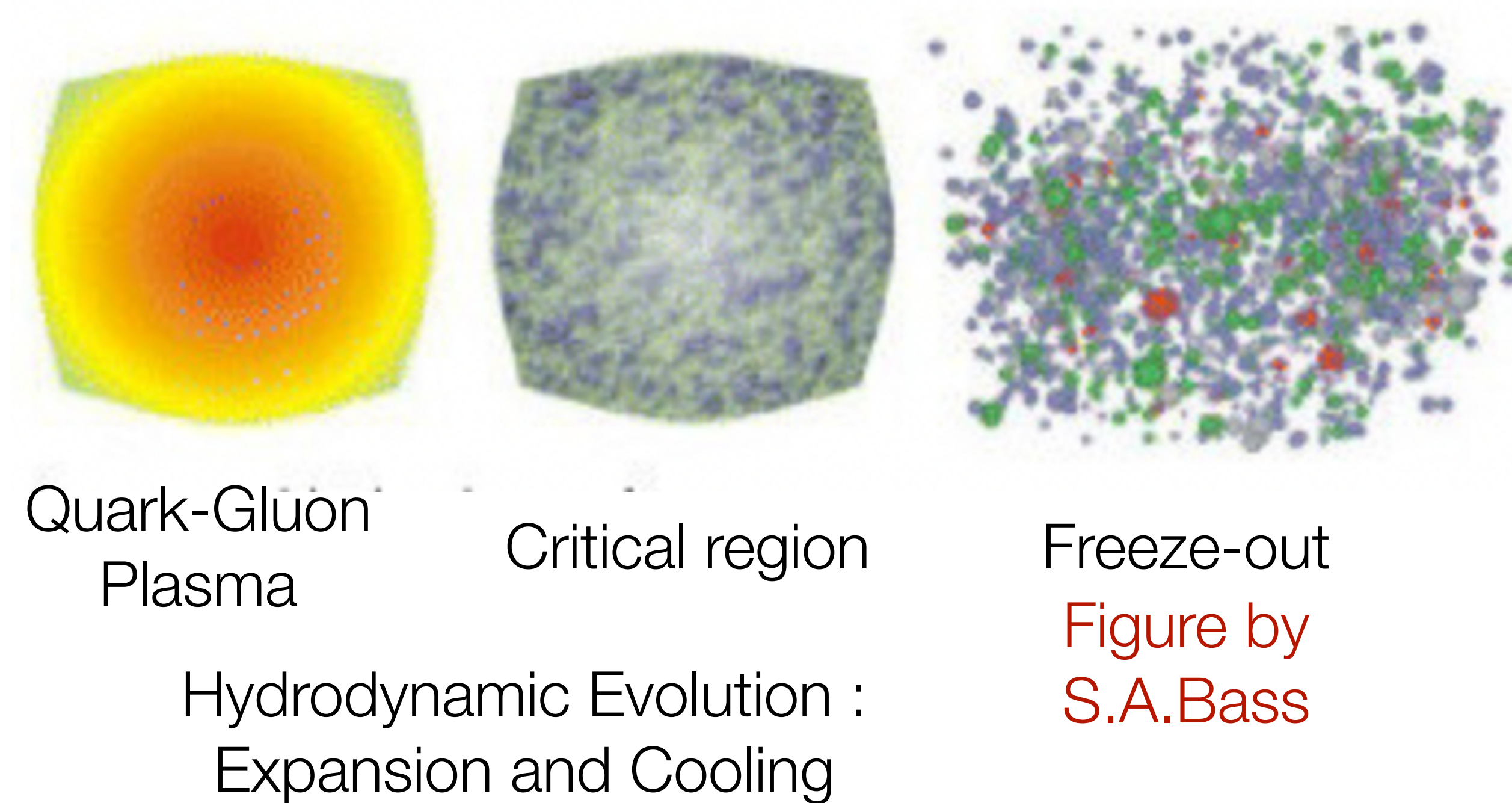
Phase diagram of Quantum Chromodynamics



- Map of singularities of the Equation of State , $P(\mu, T)$
- At $\mu_B = 0$: It is a cross-over.
- At $T = 0$: Models predict a first order phase transition

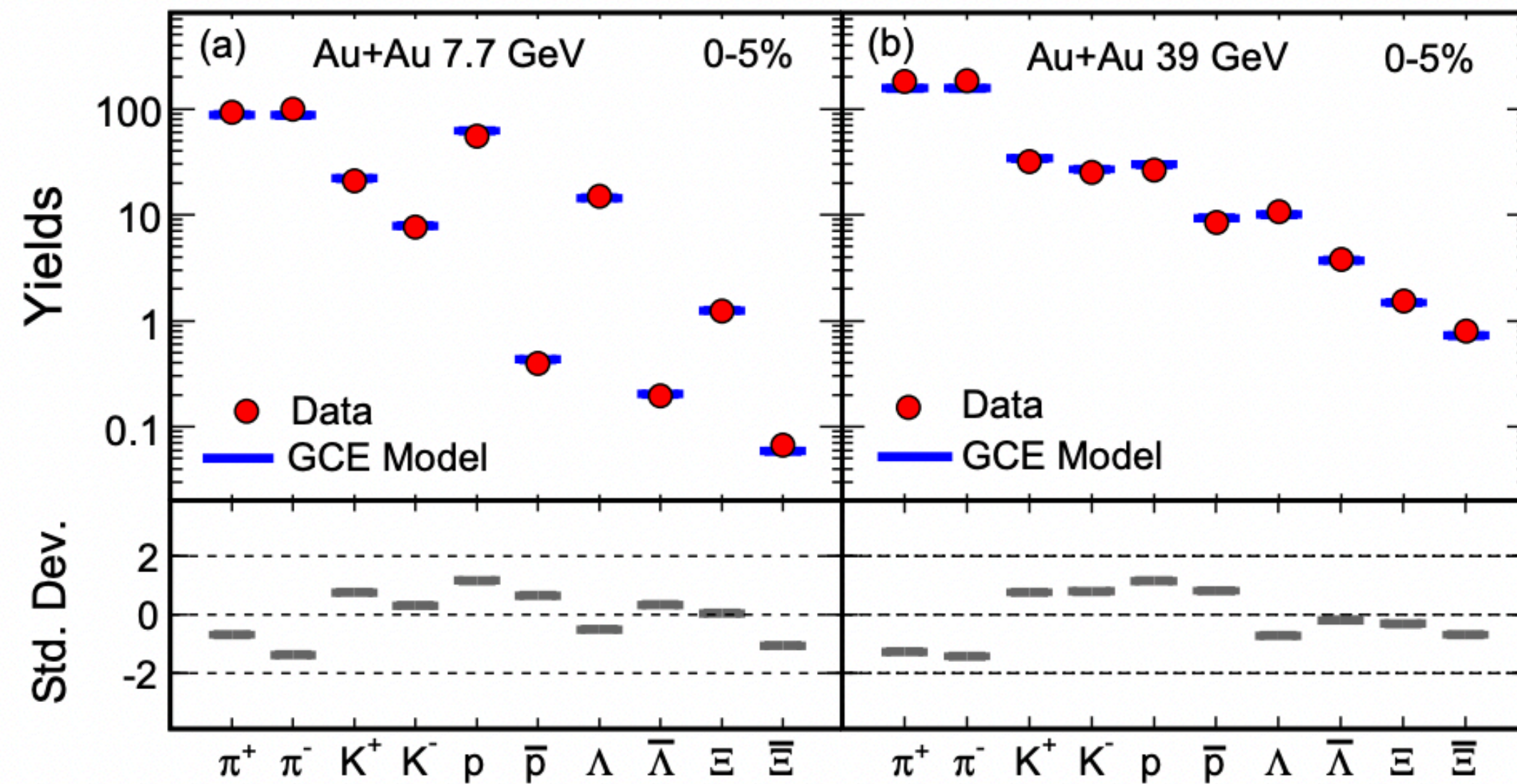
Heavy-ion collisions at varying center of mass energies can scan the phase diagram

Probing the EoS via heavy-ion collisions

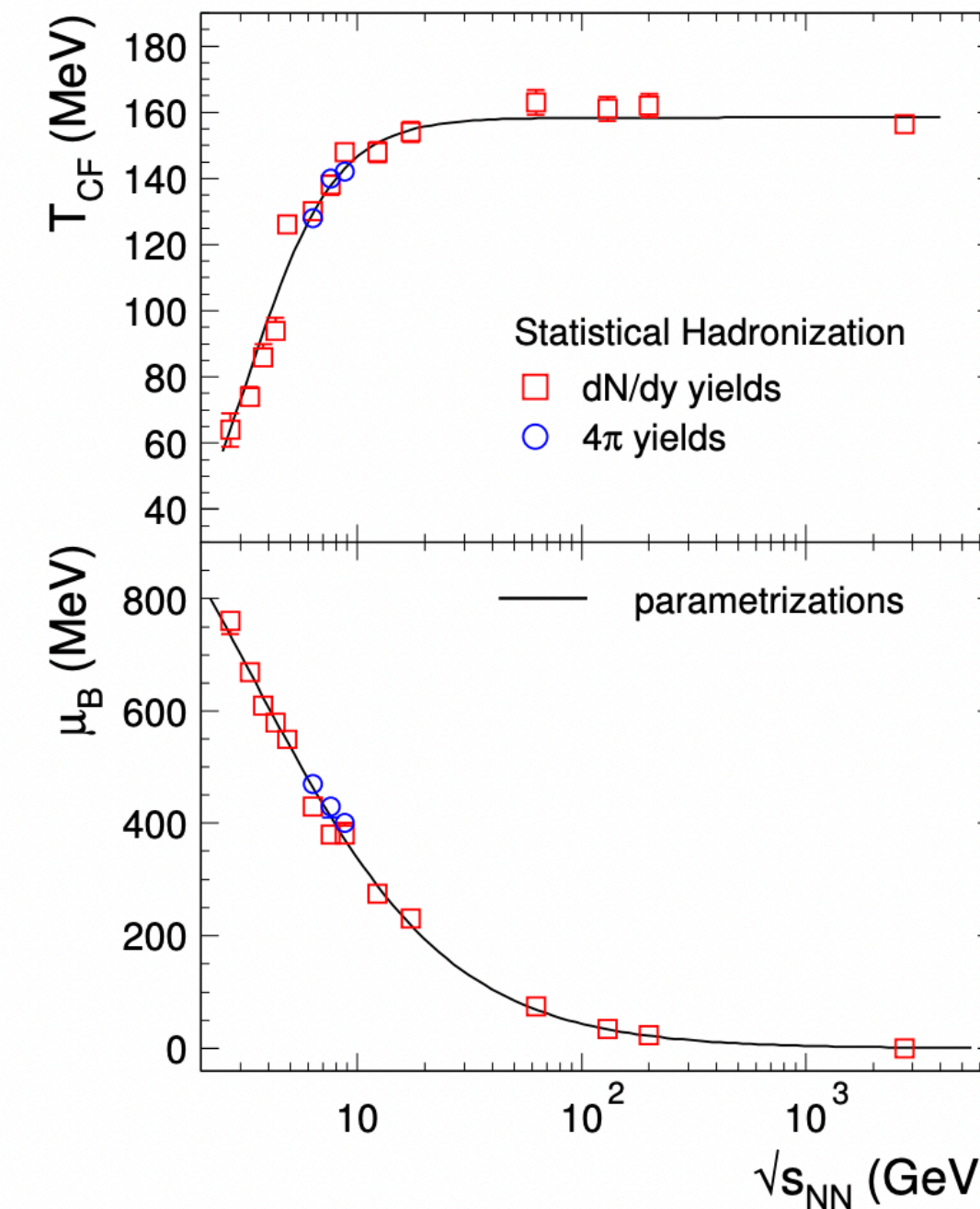


- QGP thermalizes in a relatively short amount of time $\sim 1 \text{ fm}/c \sim 10^{-24} \text{ s}$
- Freeze-out at about $10 \text{ fm}/c \sim 10^{-23} \text{ s}$
- The event by event distribution of the particle multiplicities are frozen at freeze-out and are measured at the detectors.

Hadron Resonance Gas at freeze-out



STAR Collaboration, Phys. Rev. C 96, 044904 (2017)

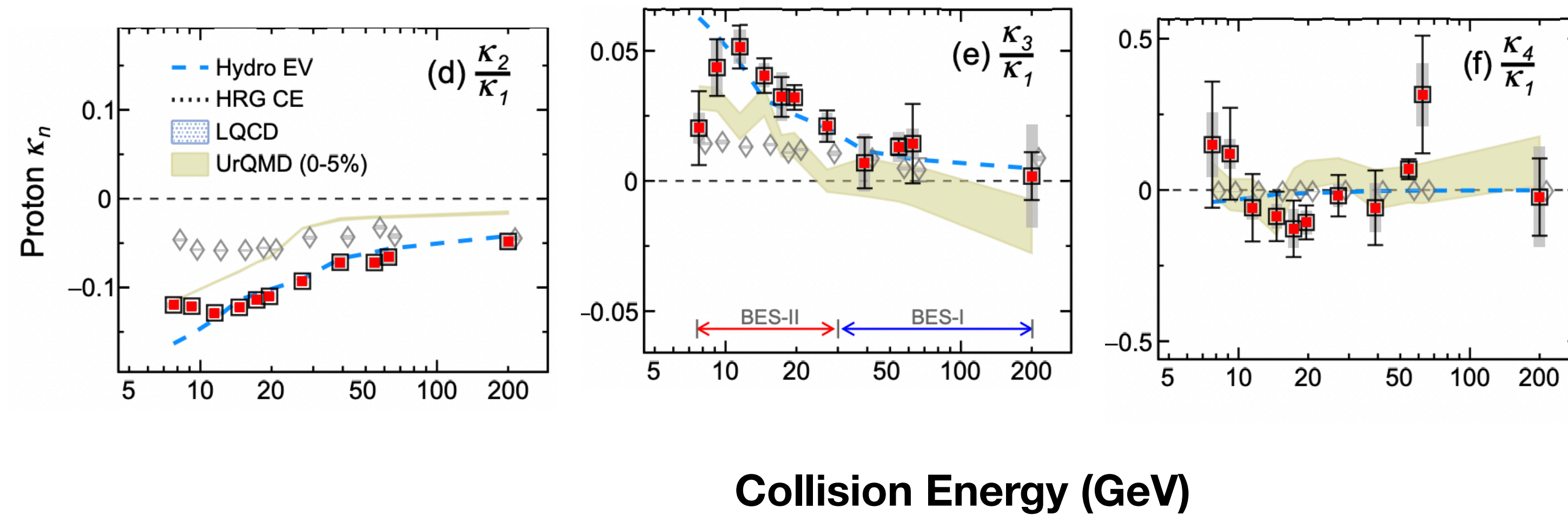


Andronic et al., Nature, 2018

- Mid-rapidity yields consistent with a Statistical Hadron Resonance Gas model
- What about event-by-event fluctuations?
- Deviations from a quantum gas of hadrons can be due to non-trivial EoS, CP, non-equilibrium dynamics etc..

Quantifying critical proton multiplicity fluctuations

Non-monotonic deviation of cumulants of proton multiplicity are characteristic signatures of the critical point - **M Stephanov, 08, PRL**



arXiv: 2504.00817, STAR, PRL

Goal : EoS near CP from data

$$\widehat{\Delta} \omega_k = \frac{\widehat{\Delta} \langle (\delta N)^k \rangle}{\langle N \rangle}$$

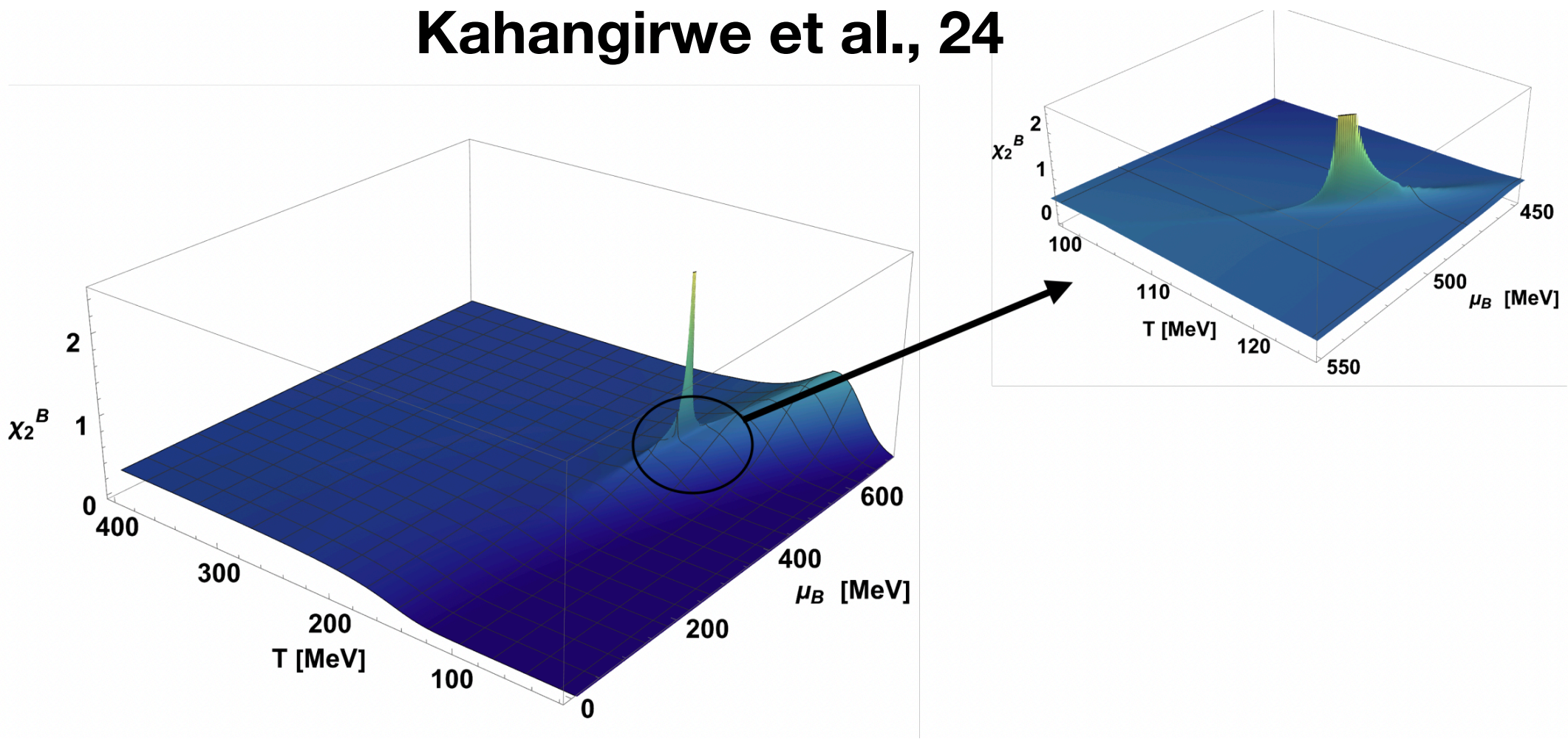
Factorial cumulants subtract the contribution that arise from trivial self correlations.

Thermodynamic fluctuations as signatures of critical point

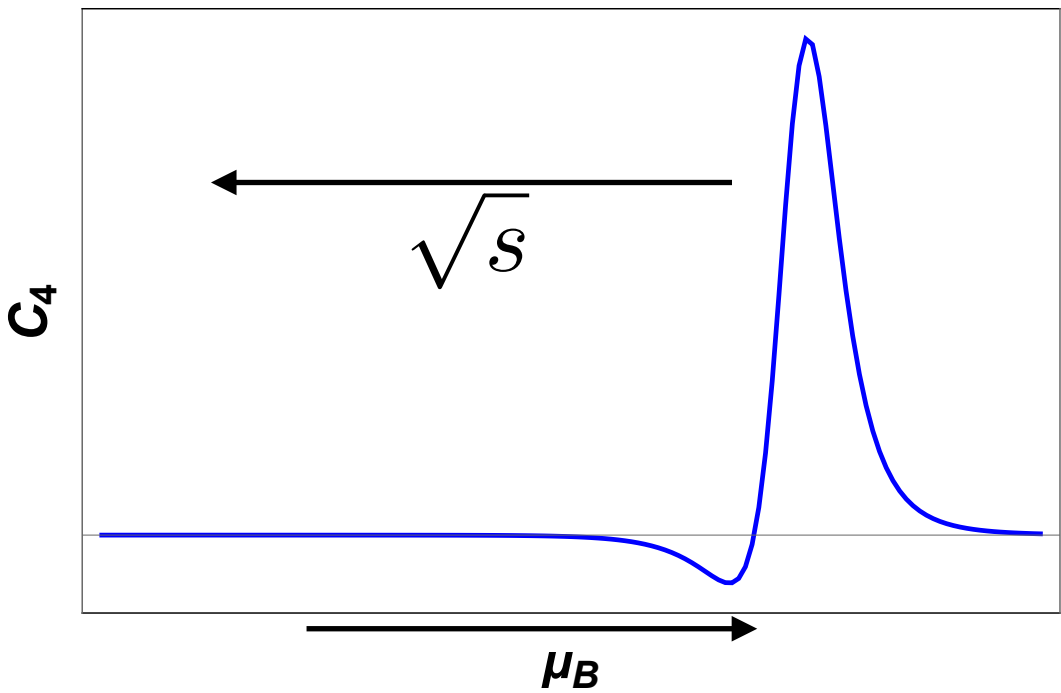
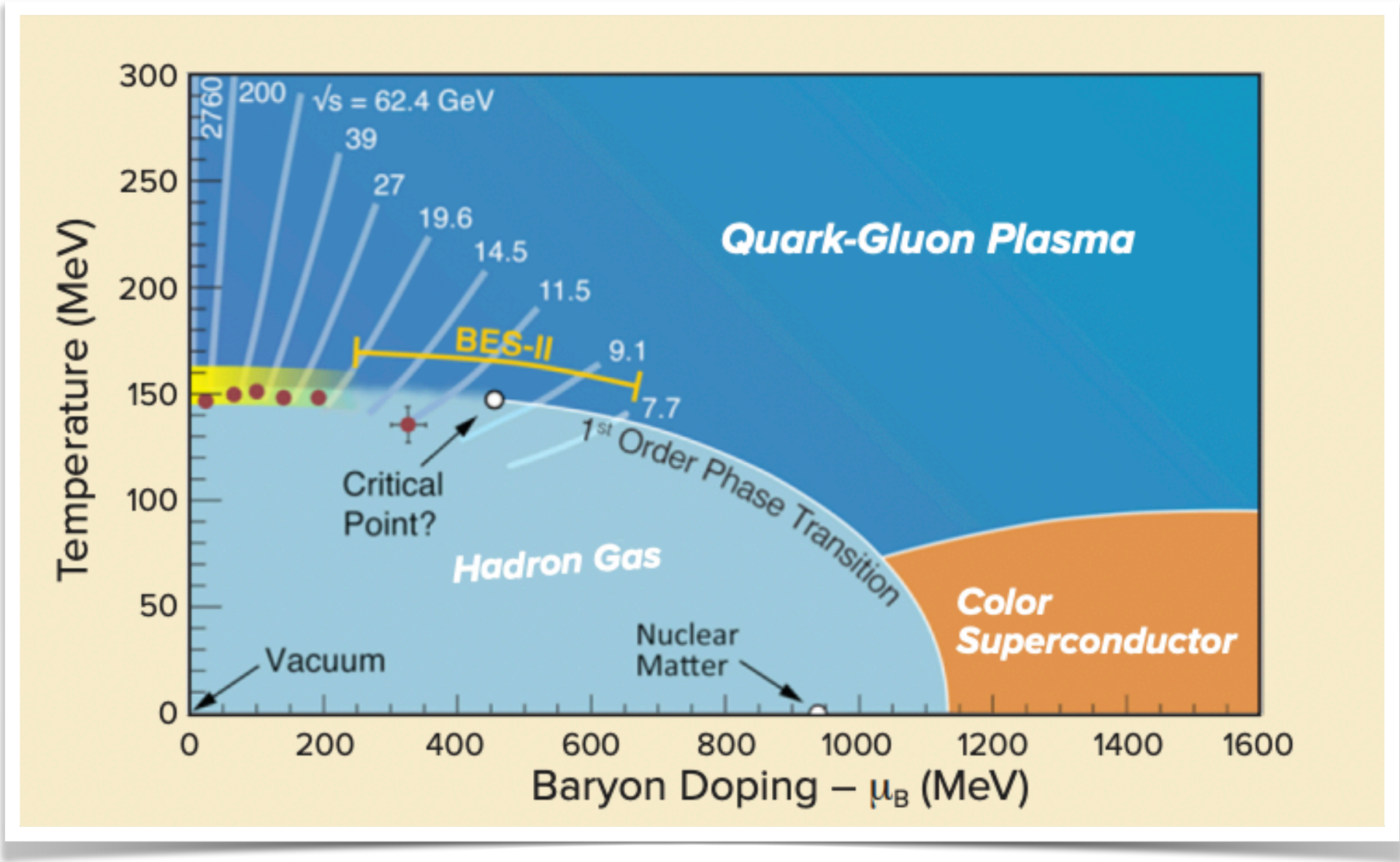
Diverges at CP

$$C_k \equiv \langle \delta N_B^k \rangle_c \stackrel{\text{in eq.}}{=} V T^{k-1} \frac{\partial^k P}{\partial \mu^k}$$

Fluctuations are enhanced near CP



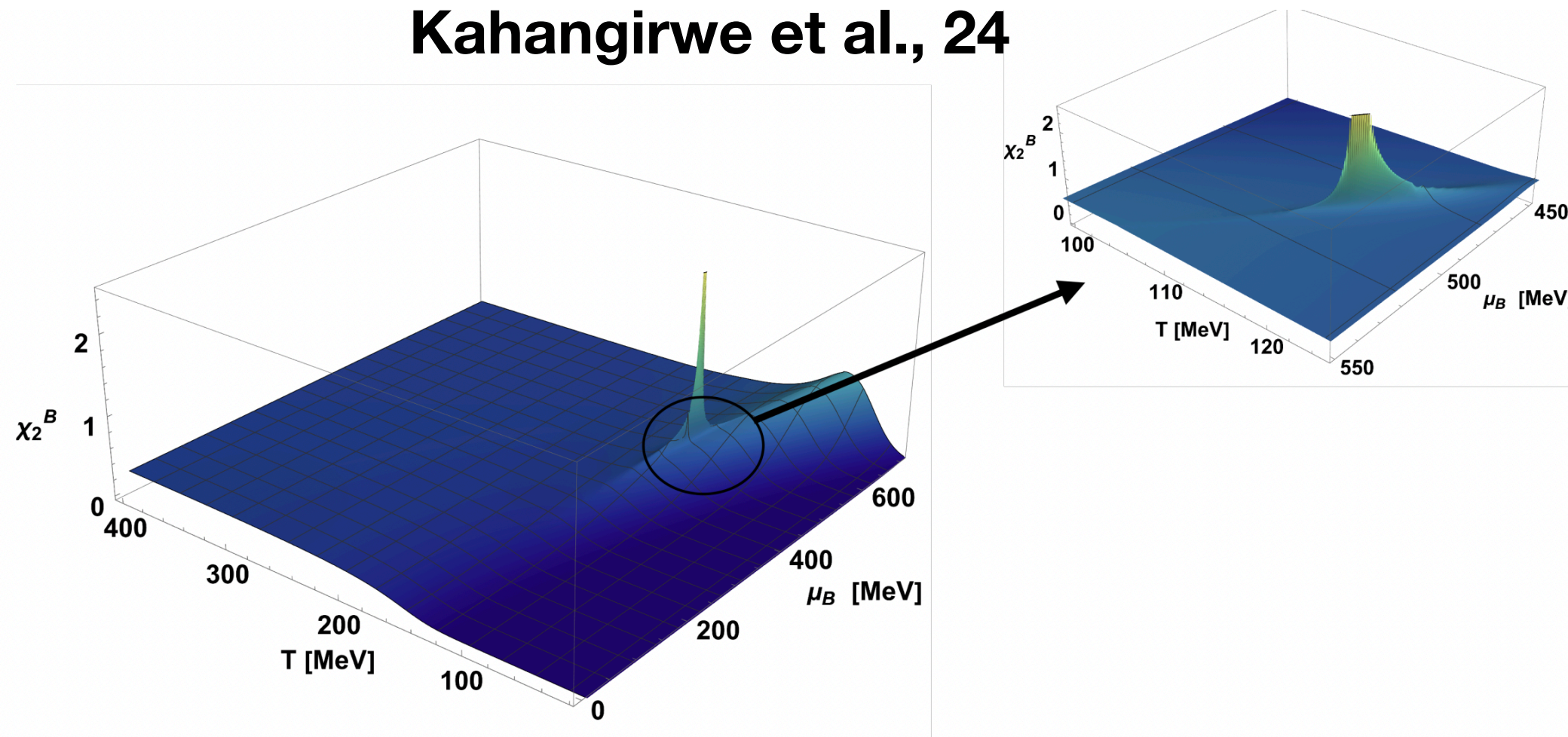
Susceptibilities that diverge at CP



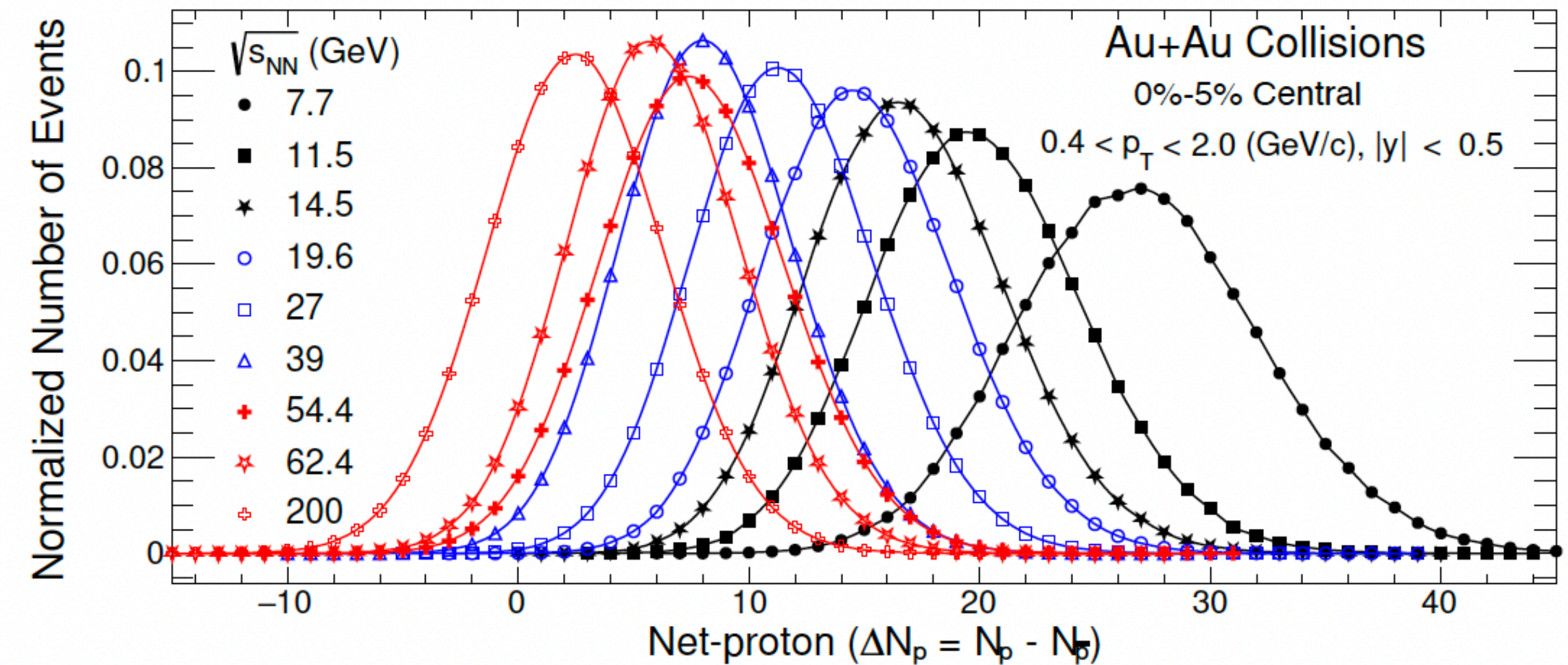
Rajagopal, Shuryak, Stephanov, 98, 99, Stephanov, 09

EoS $\longleftrightarrow$ Particle multiplicity distributions

Kahangirwe et al., 24



Susceptibilities that diverge at CP



Imprints on Particle Distribution Functions?

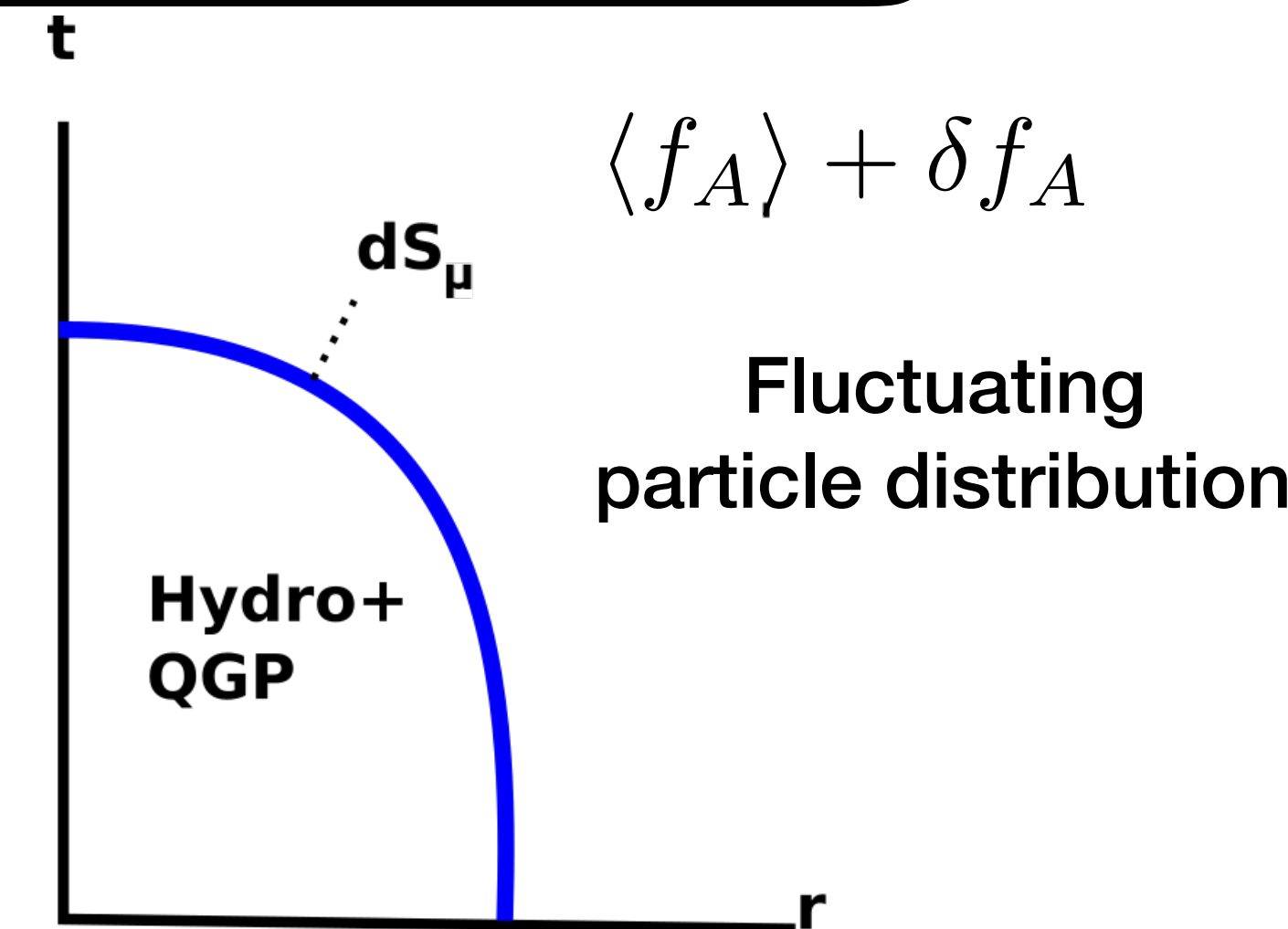
STAR Collaboration, PRL 2014, PRL 2021

Freeze-out based on maximum entropy principle

MP, Stephanov, PRL, 23

Hydrodynamics + Correlation Functions $\rightarrow$ HRG Ensemble with non-trivial phase space correlations

- Hydrodynamics + Correlations contain information about critical EoS
- Infinitely many ensembles that would match with hydro+correlations
- Cooper-Frye (74) maximizes thermodynamic entropy of HRG
- We maximize the *nPI entropy* of the HRG ensemble with fluctuations subject to matching conditions

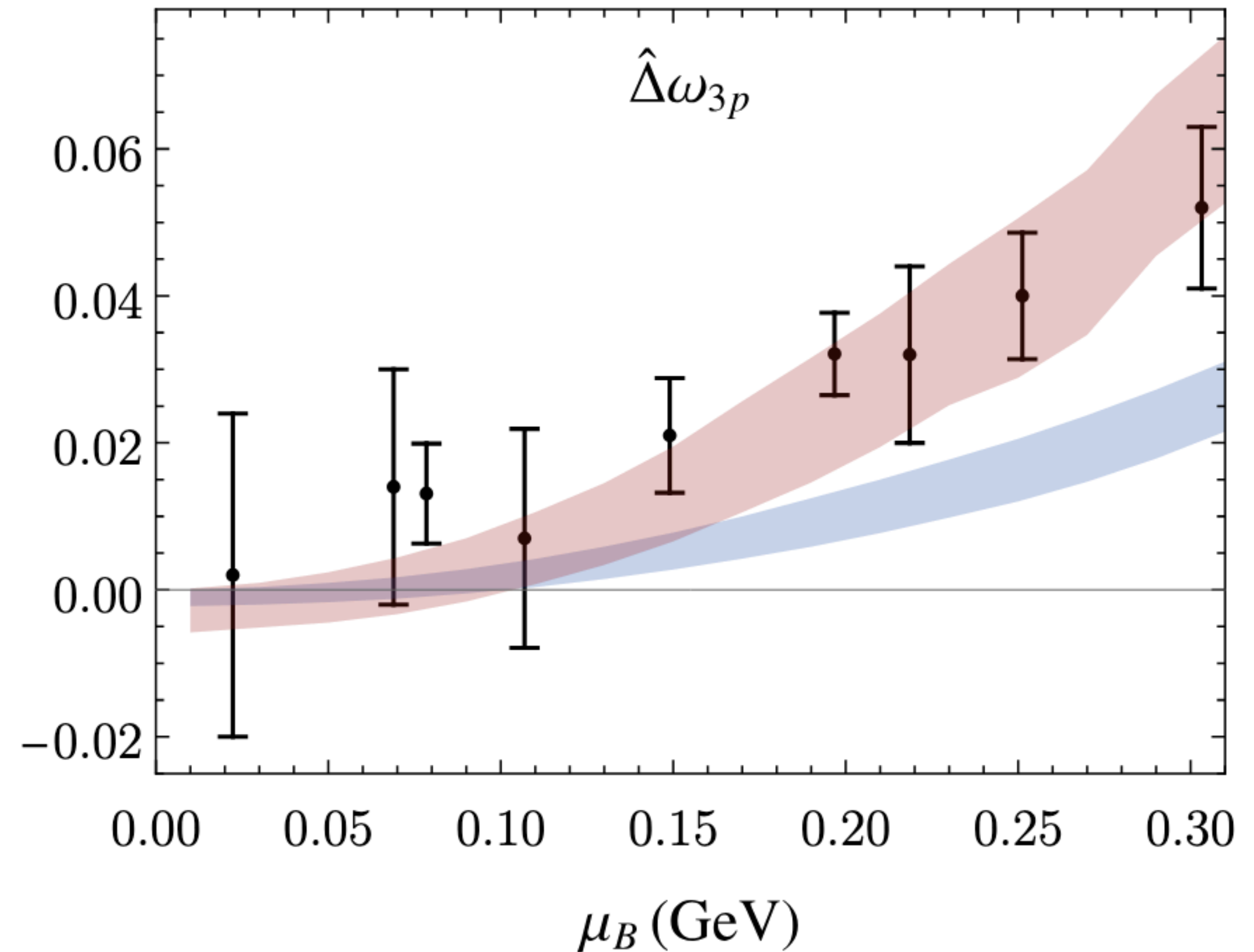
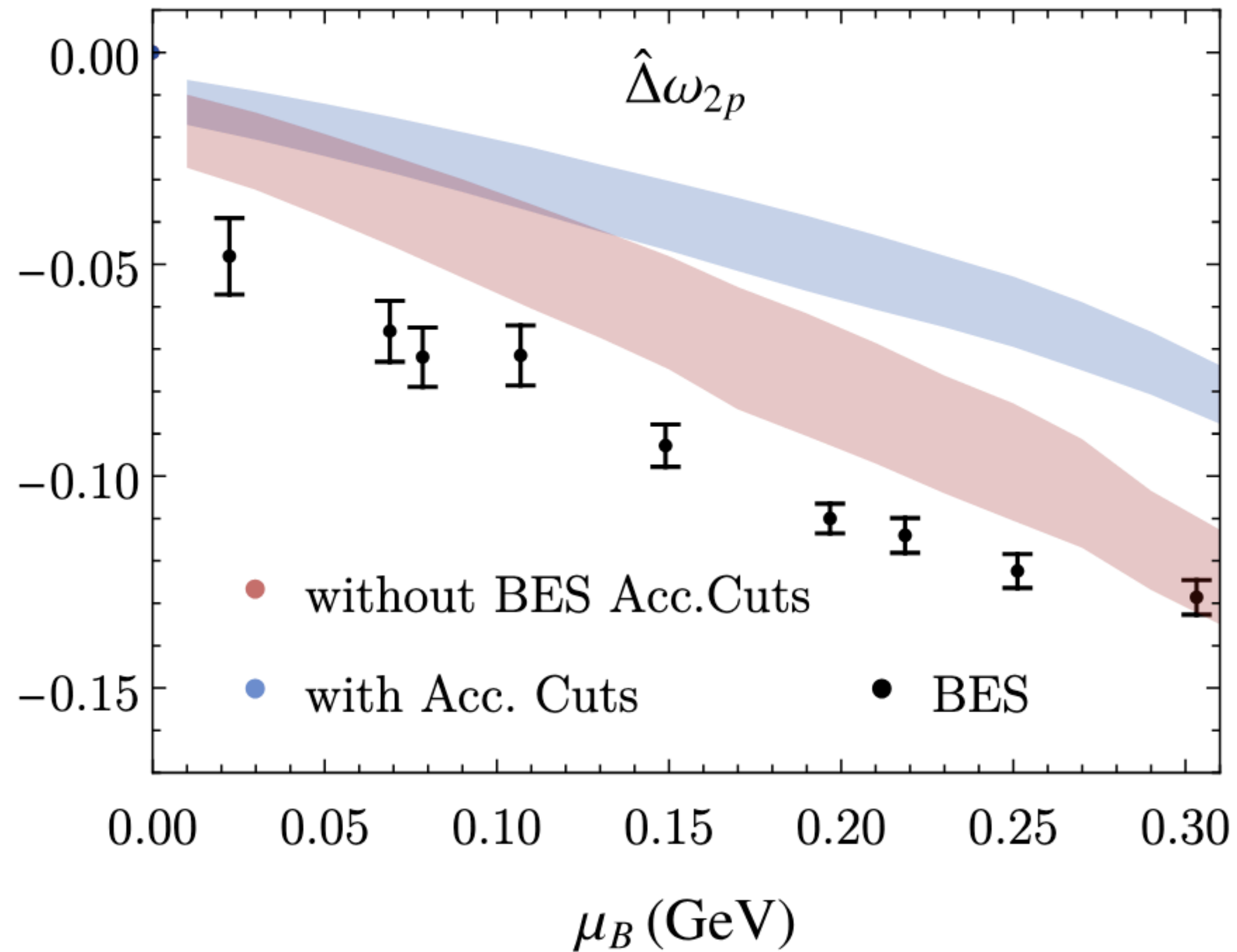


ME gives least biased ensemble of HRG that matches with hydro+correlations

Translating QCD EoS from lattice calculations into experimental observables

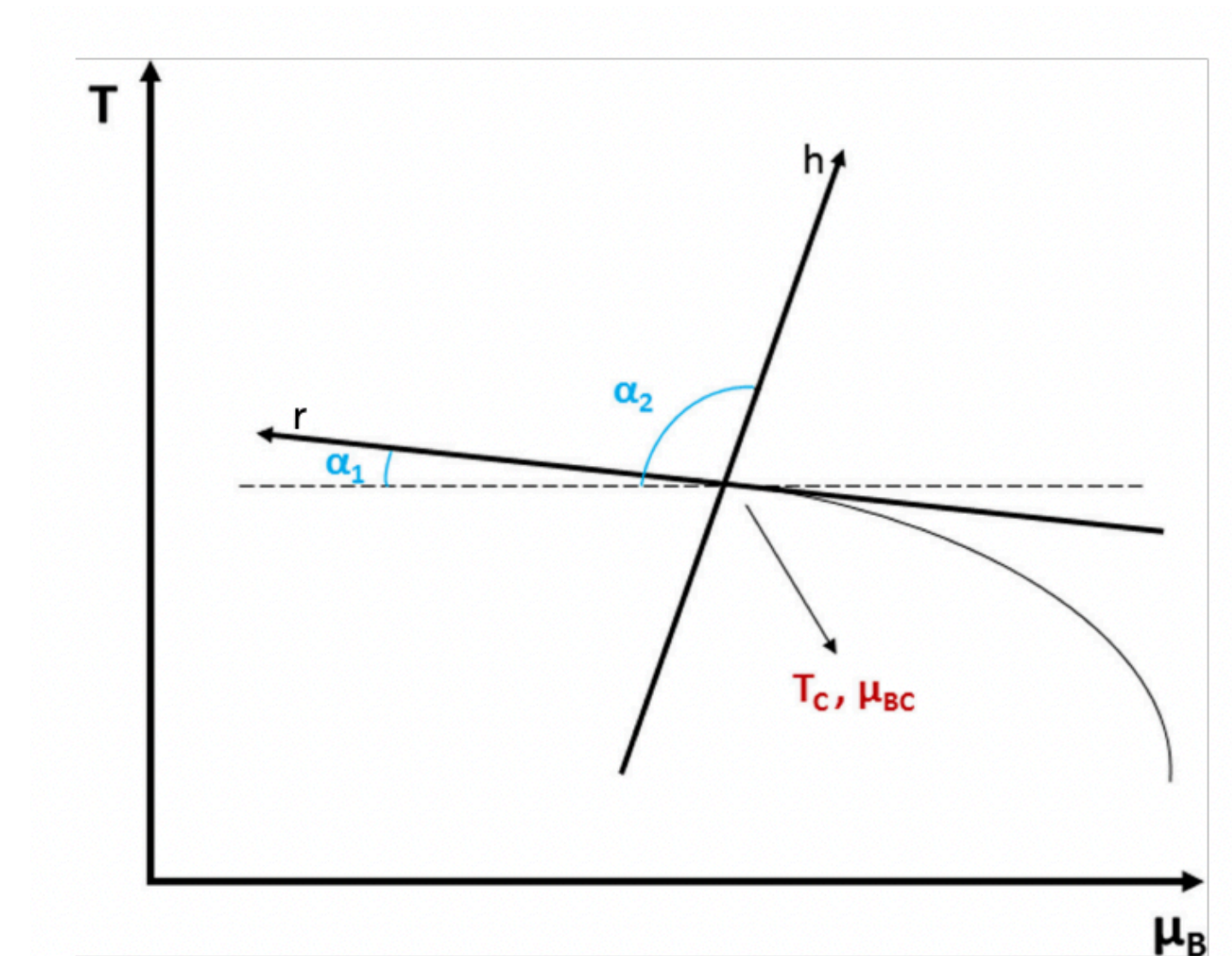
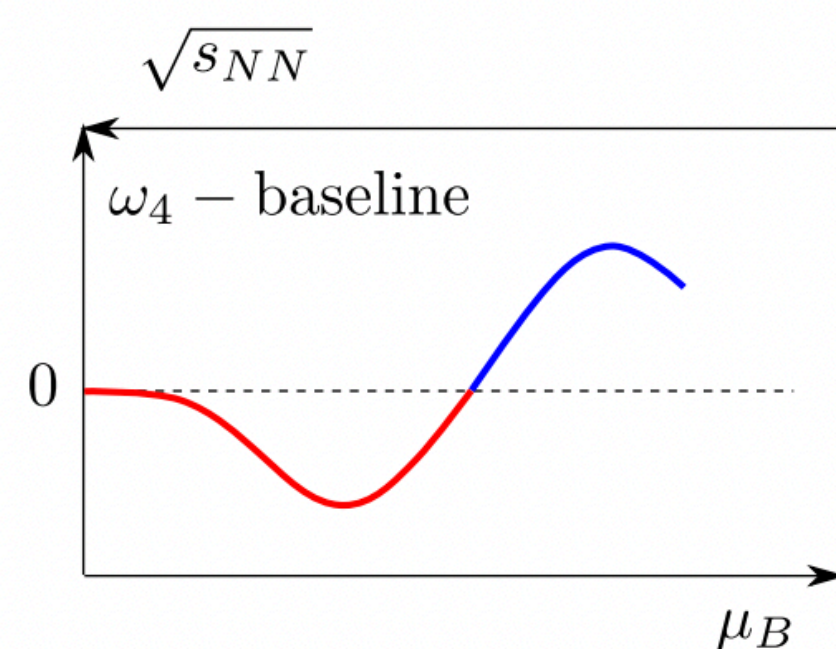
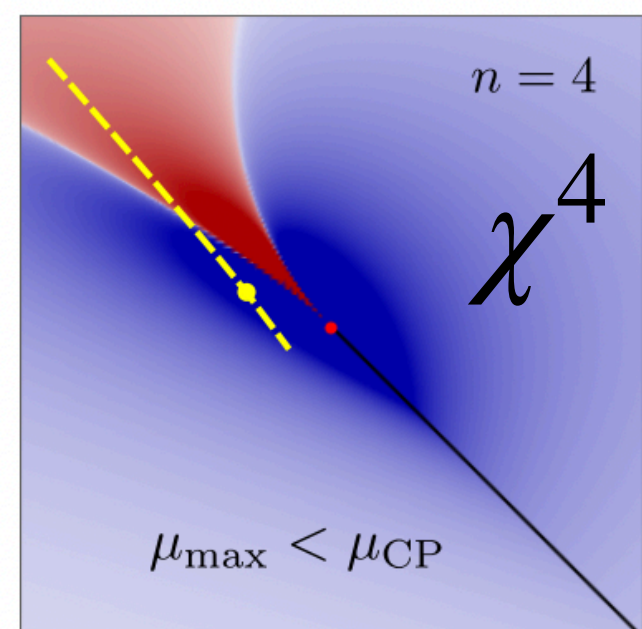
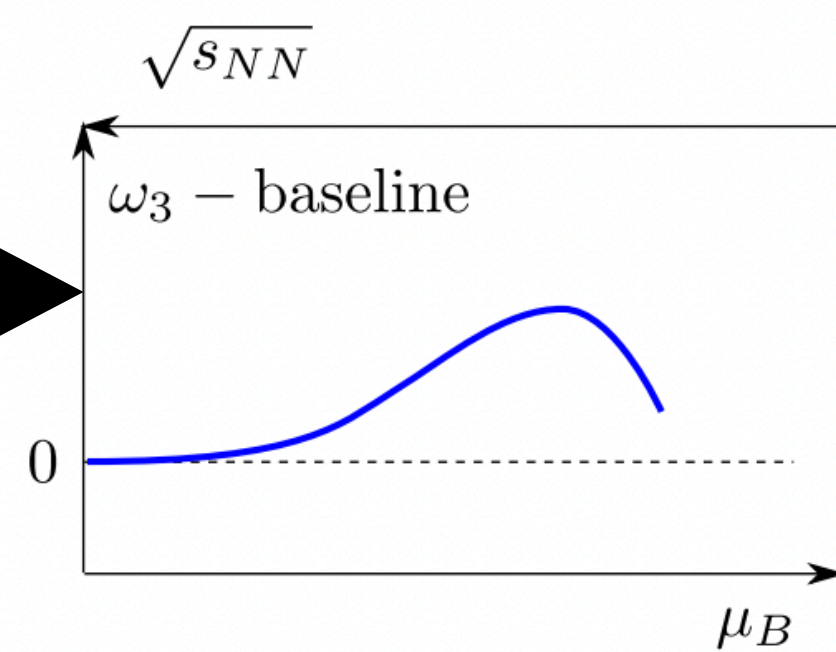
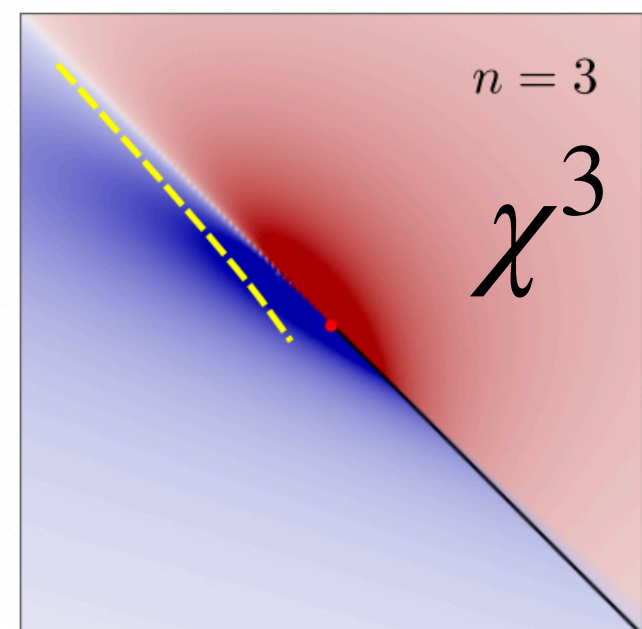
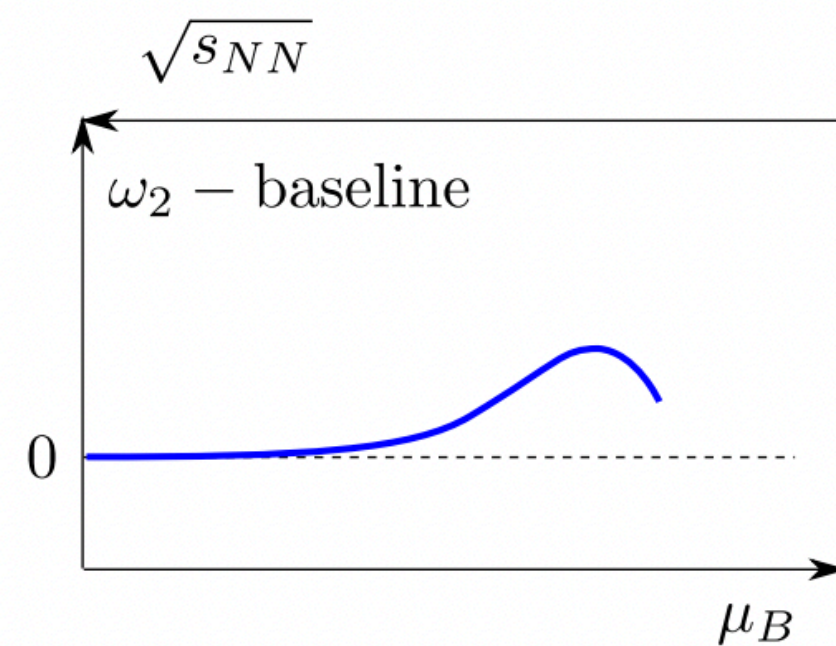
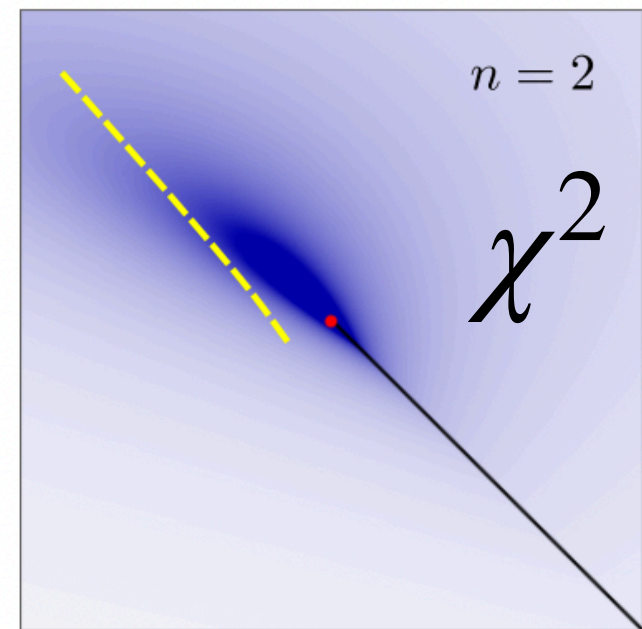
Basar, MP, Stephanov (In preparation)

arXiv : 2608.01957



Quantifying critical proton multiplicity fluctuations in equilibrium

M. Stephanov slides, SQM 24



QCD critical point falls in the 3D Ising universality class

MP, Stephanov , PRD 19
Parotto et al., 20, PRC,
Kahangirwe et al., 24 PRD

Karthein, MP, Rajagopal, Stephanov, Yin, PRD 26
Basar, MP, Stephanov, PRD 26

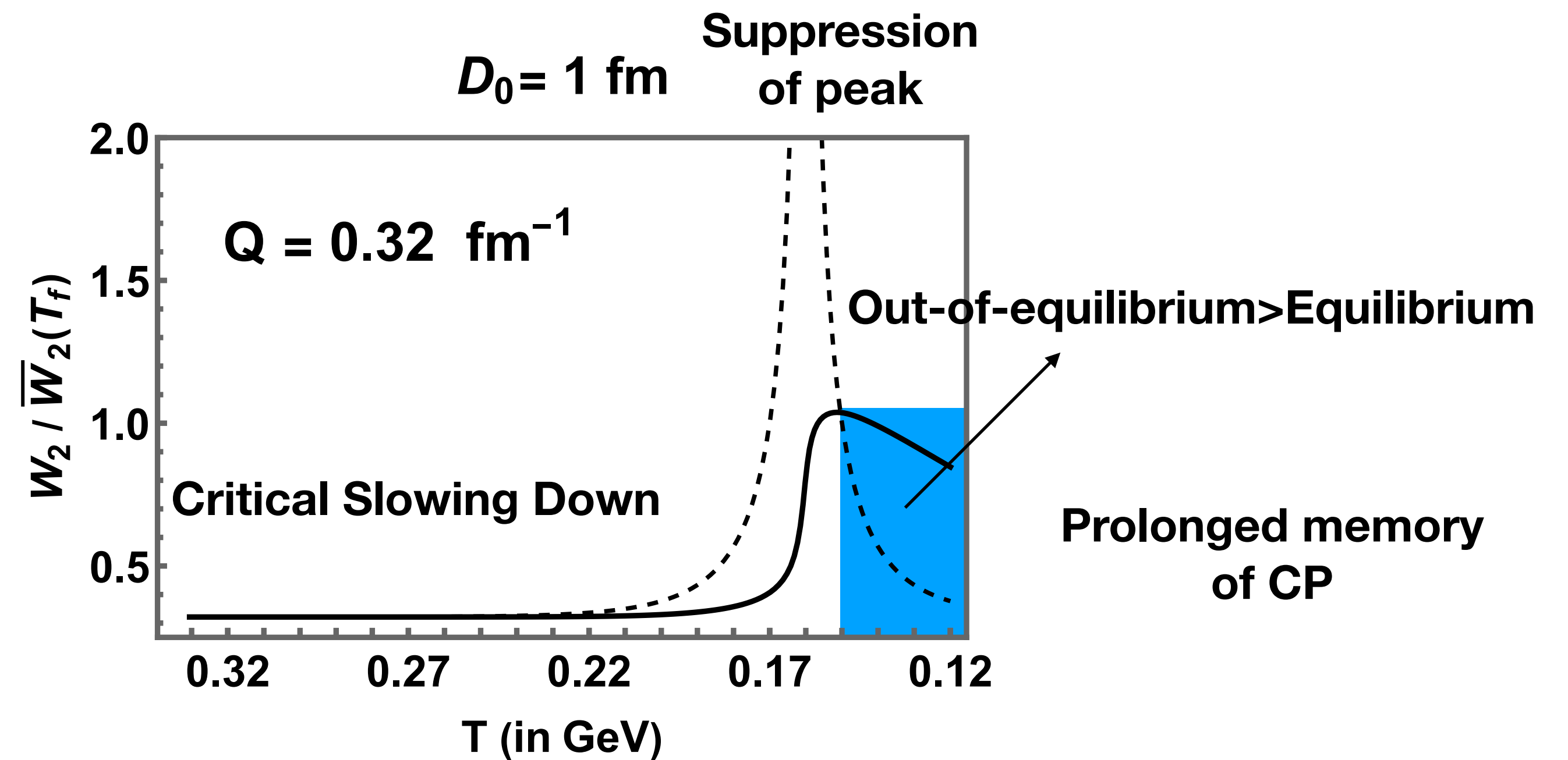
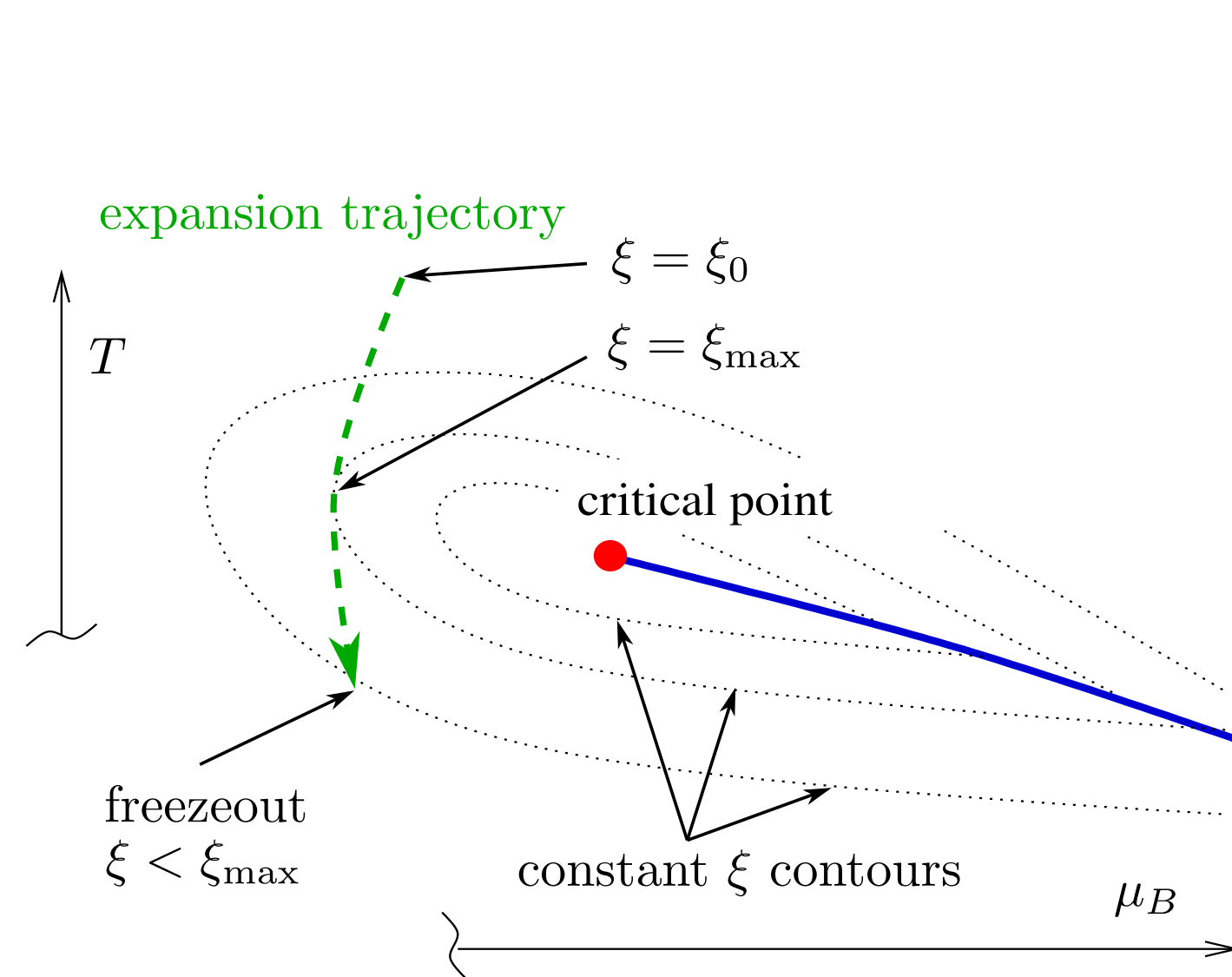
Baryon susceptibilities from
3D Ising-like EoS

Factorial cumulants of particle
multiplicity

Out-of-equilibrium effects of fluctuations near the CP

$$\langle \delta \hat{s}(x_+) \delta \hat{s}(x_-) \rangle = \int e^{i\mathbf{Q} \cdot \Delta \mathbf{x}} W_2(\mathbf{Q}), \quad \Delta \mathbf{x} = x_+ - x_-$$

Persistence of critical imprints in the fluctuation observables until freeze-out



MP, Rajagopal, Stephanov, Yin, PRD, 22

Summary

- Search for the QCD critical point remains a major experimental and theoretical challenge.
- Fluctuations provide the most promising signatures of critical behavior.
- Hybrid theoretical framework comparisons against experimental data required
- Goal : Constrain the EoS near CP and place bounds on its location